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ON THE USE OF ADAPTIVE OPTIMAL CONTROL TO PROVIDE ENERGY CONSERVATION IN LARGE BUILDINGS*

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Summary

The use of an adaptive linear regulator approach for controlling heating, ventilating, and air-conditioning (HVAC) systems in large buildings is discussed. The control manifestations of this approach are compared with those found in conventional applications. The salient features of the approach are discussed, and simulation results are presented. Implementation is discussed, and economic estimates for commercial use of this approach are also presented.

Introduction

The subject of cost-effective and energy-conserving control strategies and their implementation in building HVAC systems is widely discussed. It is generally agreed that the way a building is operated has a significant impact on energy use and that a poorly operated building can defeat even the best energy-conserving designs. It is also accepted that the use of controls, advanced when compared to present practice, will lead to improved system efficiencies.

An implicit element in the dialogue on HVAC control systems is that a systems approach must be used. The entire system, with its dynamic coupling and interplay of subsystems, must be examined to make effective control improvements. It is doubtful that today's "conventional" controls, designed in an era of inexpensive energy, were ever considered to be optimal except perhaps in the sense of their initial cost. Even if each individual subsystem (chiller, air-handling system, etc.) has a control system designed to optimize its performance and energy use, it is well known that combining them in a single system does not necessarily result in a system that optimizes overall performance and energy use.

Since 1976, personnel at the Los Alamos Scientific Laboratory (LASL) have been studying the use of adaptive and optimal control techniques in solar heated and cooled buildings[1-8]. This study has led to the development of a specific approach designated as adaptive optimal control (AOC). In this study, theoretical and computer simulation studies using the AOC concept indicate that substantial energy savings can be realized. As the AOC concept has been refined, it has enjoyed increased confidence in its ability to improve energy conservation and system performance. Various stages of development have produced simulations with substantial auxiliary energy (back-up energy needed for the solar system) savings over the conventional controller simulated in the system. Other experiments in optimizing the control strategies in the solar heated and cooled Los Alamos National Security and Resources Study Center (NSRSC) demonstrate emphatically that a considerable amount of energy can be saved by modifying conventional control hardware and, most importantly, by reviewing the control function from a system level [9].

The system-level AOC approach is discussed here from a conceptual point of view. Simulation results are presented, and implementation is discussed from both hardware and economic perspectives.

AOC Concept

To illustrate the AOC concept, consider the portion of a solar heating system shown in Fig. 1. There the controls to be determined are (1) the hot water flow rate, W_{hw}, (2) the choice of the storage tank or the auxiliary heat exchanger as an energy source, and (3) the temperature, T_{aux}, of the auxiliary energy source if it is chosen. Conventional strategies for determining these controls are also shown in Fig. 1. The hot water flow rate is determined solely on the basis of the room temperature, T_r. In determining the flow rate, no consideration is given to the temperature of the water and, therefore, to its ability to heat the room. The choice of the solar storage tank or the auxiliary heat exchanger as the source of energy

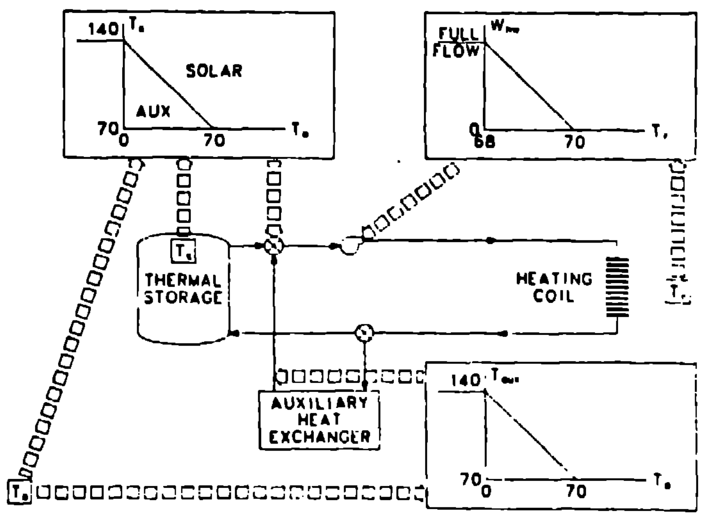

Fig. 1. Conventional control strategy.

*This work has been supported by the Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, US Department of Energy.

is based on the storage tank temperature, T_s, and the ambient temperature, T_a. Certainly, the ambient temperature affects the room temperature, but the room temperature is not explicitly considered. Similarly, the auxiliary hot water temperature is determined solely by the ambient temperature and does not consider the actual room heating requirements as reflected in the room temperature.

The AOC approach, however, considers all the significant system variables in determining the controls as schematically illustrated in Fig. 2. The block diagram of Fig. 3 shows the AOC components and their functional interaction. The building (or plant) represents the nonlinear dynamics of the building and entire HVAC system. The model identification block represents the sequential least squares system identification process, which identifies a linear model that accurately reproduces the nonlinear plant behavior for the given set of operating conditions. Once the linearized parameters have been identified, they will be used in conjunction with an integral quadratic cost functional to compute the optimal controller parameters (gains and offsets). The computation of the optimal control parameters also uses optimization data from a portion of the system known as the supervisor. The optimization data it provides contain such information as set points, modifications to the relative weights in the performance index and system adjustments based on the time of day. The supervisor also provides a channel to communicate any human operator's commands to the system. The controller computational algorithm makes use of standard linear regulator/linear servomechanism theory with set points for both the control and state variables. The controller uses the control parameters to generate the appropriate closed-loop control to minimize the cost functional. The model identification process is an on-line process; after a fixed amount of time, it will have an updated linear model available. That updated linear model and the optimization data supplied by the supervisor are then used to recompute the optimal control law. The control system is, therefore, changed (adapted) to remain optimal as the system undergoes changes of various forms.

The control parameters are used to implement linear, closed-loop control equations such as

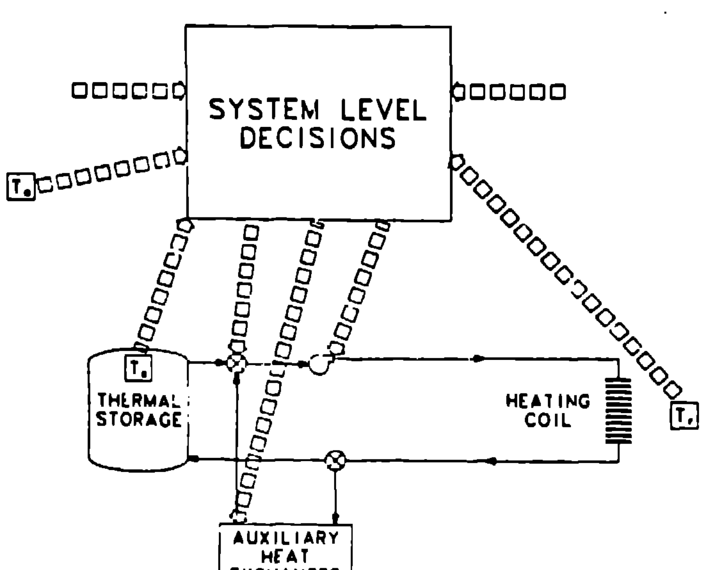

Fig. 2. AOC strategy.

$$W_{hws} = k_1 T_r + k_2 T_s \dots + \xi \ , \qquad (1)$$

where W_{hws} is the hot water flow rate out of the storage tank, and ξ is an offset. Closed-loop control equations are essential for any HVAC control process to be implemented.

Some of the features of the control equations are depicted in Fig. 4. Fig. 4(a) shows the multidimensional characteristics of Eq. (1). The hot water flow rate is a function of more than one of the system variables. Both the room temperature <u>and</u> the storage tank temperature, as well as other system variables that would be visualized in a higher order space, determine the hot water flow rate when the storage tank is being used. If all of the variables but one, say T_r, are chosen at some constant value, then W_{hws} becomes the same type control equation the conventional controller uses. Continuing to examine W_{hws} as a function of T_r only, the slope of the line between saturation limits is the controller gain, k_1. The adaptive nature of the AOC approach is manifested when the entire process is repeated periodically, and the resulting gains are subject to change as shown in Fig. 4(b). A plot of a single gain as a function of time might appear as in Fig. 4(c). The preceding discussion has concentrated on W_{hws} as a function of T_r, but similar comments apply to all the variable terms in Eq. (1). In fact, the multidimensional plane of Fig. 4(a) would change each time the system adapts (or is updated).

One readily sees then that the <u>type</u> of control offered by the AOC is essentially that found in a conventional proportional controller. However, the control parameters are determined using a system-level approach; and further, they are optimally determined to minimize a specific performance index.

<u>Simulation and Results</u>

Operation of an AOC controller has been simulated on a digital computer and compared with operation of a conventional controller, also simulated on a digital computer. The simulations have shown that the AOC can achieve substantial auxiliary energy savings when compared to the conventional controller while regulating the room temperature quite well.

The NSRSC at LASL provides the basis for a general model used in this simulation. The NSRSC is a 59,000 ft^2 library and conference facility. It has both

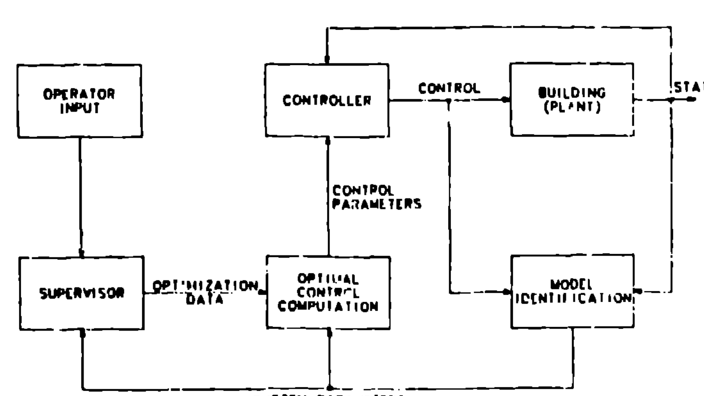

Fig. 3. System block diagram.

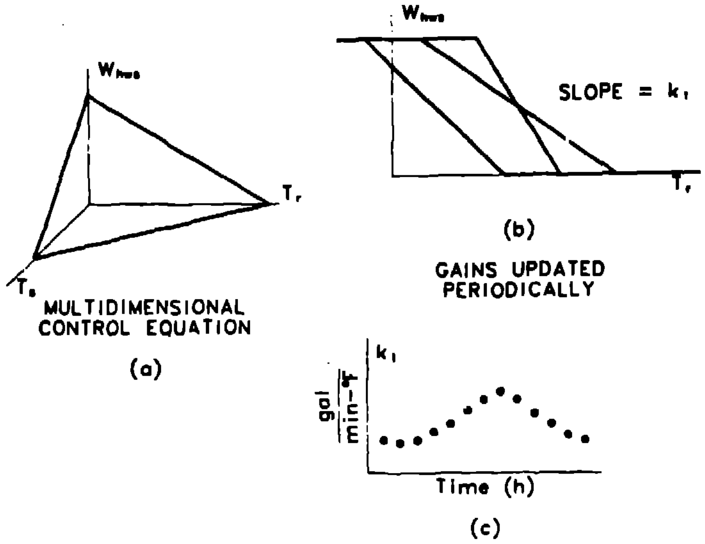

Fig. 4. Control equation features.

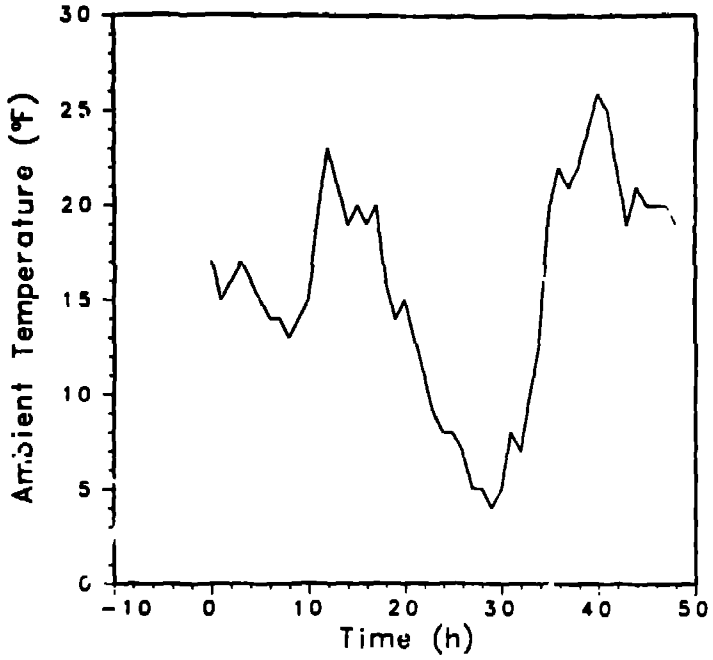

Fig. 6. Ambient temperature for short-term simulations.

solar heating and cooling systems, but only the heating system is discussed here. A simplified model of the solar heating system used is shown in Fig. 5.

Short-Term Results

Initial simulation of the AOC operation was for 1- and 2-day periods. The days selected were rather cold but sunny as shown in Figs. 6 and 7. Performance under these conditions is summarized in Table I. The "conventional controller" simulation uses the control strategies of the NSRSC. The "AOC-mixing" simulation uses the AOC technique with the two energy sources capable of being used simultaneously through a mixing valve arrangement. The "AOC-exclusive" simulation uses the AOC technique with the two energy sources used in a mutually exclusive fashion. All the control systems simulated maintain the room temperature within a comfortable range. However, the AOC technique simulations do so with a significantly smaller amount of auxiliary energy and result in an auxiliary energy savings of as much as 51%.

Long-Term Results

To exercise the controllers over a wide range of operating conditions, a month's operation was simulated. Weather data are shown in Figs. 8 and 9. The performance results are shown in Table II.

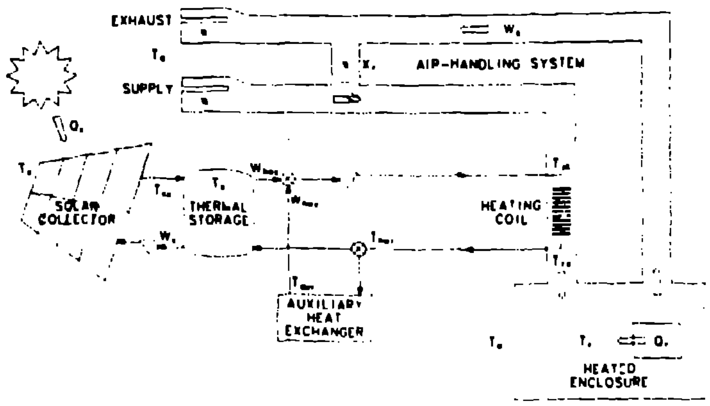

Fig. 5. Solar heating system model.

The "conventional controller" and "AOC-exclusive" simulation have the same meaning as in the short term simulation. Again, the room temperature is maintained quite well by both controllers, but the AOC controller uses much less auxiliary energy and results in an auxiliary energy savings of over 95%. It must be recalled that this is a savings in back-up energy for the solar system and not the total energy needed to heat the building. Milder weather is more conducive to total solar heating, and the increase in auxiliary energy savings is partially attributable to the milder (and more typical) weather of the long-term simulation.

In both simulations, the AOC operated the building to make better use of all available sources of energy. The emphasis on improved management of energy resources by the AOC technique is indeed appropriate.

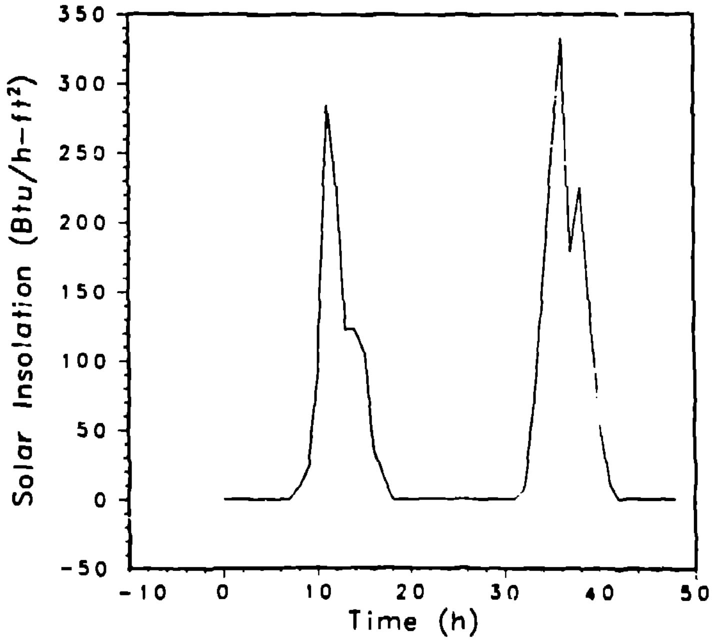

Fig. 7. Solar insolation for short-term simulations.

TABLE I

HEATING SYSTEM PERFORMANCE
SHORT-TERM SIMULATION

System	Average Room Temperature (°F)	Room Temperature Extremes (°F)	Auxiliary Energy Used (10^6 Btu)	% Savings Compared to Conventional Controller
Conventional controller	70.0	69.8 70.4	6.75	----
AOC-mixing	69.7	68.4 70.2	4.13	38.8
AOC-exclusive	69.7	67.4 70.5	3.28	51.3

Implementation

The hardware needed to implement the AOC may be considered in three categories.

1. Sensors and actuators
2. Satellite controllers
3. Algorithm processor

The role of each component is shown in Fig. 10.

Sensors and Actuators

Accurate sensing of system conditions is needed for the system identification process to determine the model and current set of operating conditions. It is important to note that fewer sensors may be needed with the AOC controller than with a conventional controller. This is because the AOC approach bases its model on a state-variable representation, and any information needed may be determined from the state, the controls, and the external inputs such as ambient temperature.

The actuators must be capable of effecting the control when commanded by digital signals. Electrically controlled valves, dampers, etc. could be used, or electrical-pneumatic transducers could be used with a pneumatic system. The sensors and actuators are not conceptually different from those found in conventional control systems. However, their placement and use in the HVAC system may be different.

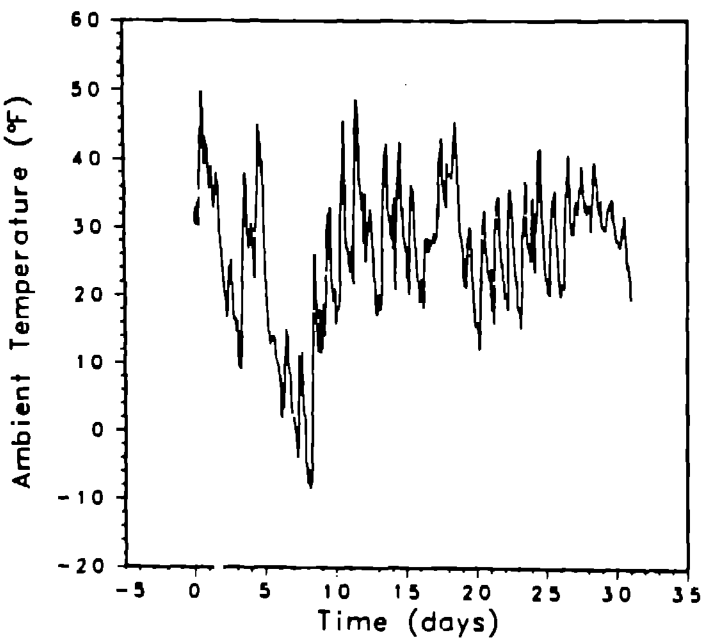

Fig. 8. Ambient temperature for long-term simulations.

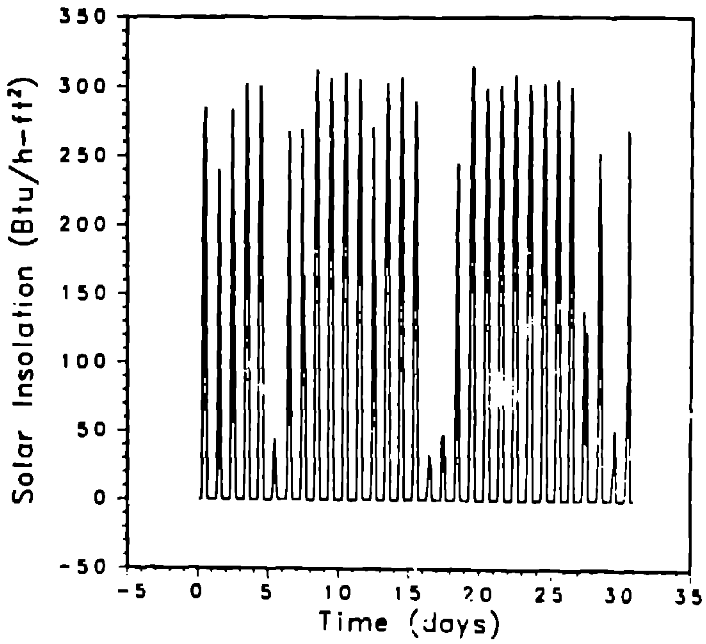

Fig. 9. Solar insolation for long-term simulations.

TABLE II

HEATING SYSTEM PERFORMANCE
LONG-TERM SIMULATION

System	Average Room Temperature (°F)	Room Temperature Extremes (°F)	Auxiliary Energy Used (10^6 Btu)	% Savings Compared to Conventional Controller
Conventional controller	70.1	68.9 70.7	13.074	----
AOC-exclusive	70.0	68.1 71.4	0.571	95.6

Satellite Controllers

The satellite controllers receive control parameters from the algorithm processor and implement the control equation. Specifically, the control gains and offsets would be transmitted. Information from the sensors is available, and the satellite controllers put the control into effect.

The satellite controllers are capable of operating without intervention from the algorithm processor. Once the control parameters have been received, they are used until they are updated upon completion of an adaptation interval. This pseudoindependent operation of the satellite controllers allows the HVAC system to continue operation if the algorithm processor should go down. The satellite controllers must have nonvolatile memory in order to provide maximum control capability in the face of control interruption.

Algorithm Processor

The algorithm processor does what its name implies: it processes the algorithms to provide the gains and offsets to the satellite controllers. It samples the sensor data periodically and computes the system model using the system identification technique. When a model is ready (at the conclusion of a fixed interval), it performs the optimal control computations and transmits the data to the satellite controllers. It then begins another interval of sampling data.

Computing Capability

A modest amount of memory will be needed by the satellite controllers to store the control parameters. A very limited amount of numerical processing needs to be done, so the speed and functional complexity required do not generate strenuous demands.

The algorithm processor is primarily concerned with numerical processing, so the demands it generates are somewhat more strenuous. A minicomputer is believed capable of doing the processing in the time necessary, and memory poses the only serious requirement. Precise estimates of memory requirements are not available, but 64,000 words is likely more than enough. This level of computing power can be accomplished with microprocessors, and recently announced devices make use of a microprocessor even more attractive.

Economic Estimates

Although the manifestations of AOC at the actuator are quite similar to the techniques in use today, the overall use of AOC for HVAC systems is a striking departure from present practice. It is therefore desirable to relate the potential benefits of the control method to applications, and these benefits are estimated in the following discussion. A number of assumptions are made that are necessary because of the many unknown factors related to the application of AOC to operating buildings.

Savings

The simulation results discussed above suggest savings in auxiliary energy for the short-term, severe weather heating case of as much as 51%; whereas, the long-term, milder weather simulation results offer an even greater auxiliary-energy savings of 95%. Of course, these results are for a solar-heated building, but the control methodology in the AOC implementation can be extended from its present limited application to any HVAC system in which control options that impact energy use exist. Such extensions have not yet been made, but it is expected that energy savings will result when this is done. The application of AOC is appropriate to those buildings with HVAC systems that

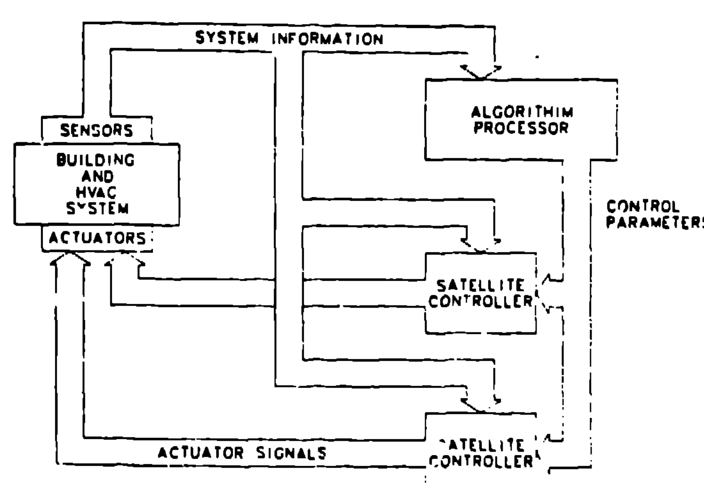

Fig. 10. AOC implementation.

include numerous control options. Such buildings exist today and will exist to a greater degree in the future as more energy saving equipment is employed.

Based on the expected performance of AOC, both as simulated by LASL and as found in process industry applications, it appears reasonable to estimate that 20% of the energy used for heating and cooling will be saved in general installations beyond that possible with effectively utilized computer-based logic systems. Based on a 20% savings in energy, the energy cost savings achievable for office buildings in the Chicago area are shown in Fig. 11 [10,11]. Because implementation is not anticipated until after additional research and development is completed, energy costs are projected to those three years from the present based on a 7% annual increase.

Additional benefits from the application of AOC may be derived from its identification process and the measures of the system states. Two of these are (1) the use of performance identification to determine when maintenance is required on specific equipment, and (2) the use of system states to determine potential causes of out-of-tolerance system conditions. Information available in the AOC implementation brings these diagnostic system features closer to reality. The actual monetary benefits of such features cannot, however, be readily determined.

Costs

At this time, the AOC method under study at LASL has only been implemented on the scientific computer facility at LASL. In this section, the cost of implementing the method in a building is estimated. Although this estimate includes a significant degree of uncertainty, the level of effort is within the scope of other work performed in the development of building automation systems. It is noted that the basic development and testing of the AOC method is not included in the costs given.

The following are assumptions for the cost estimate.

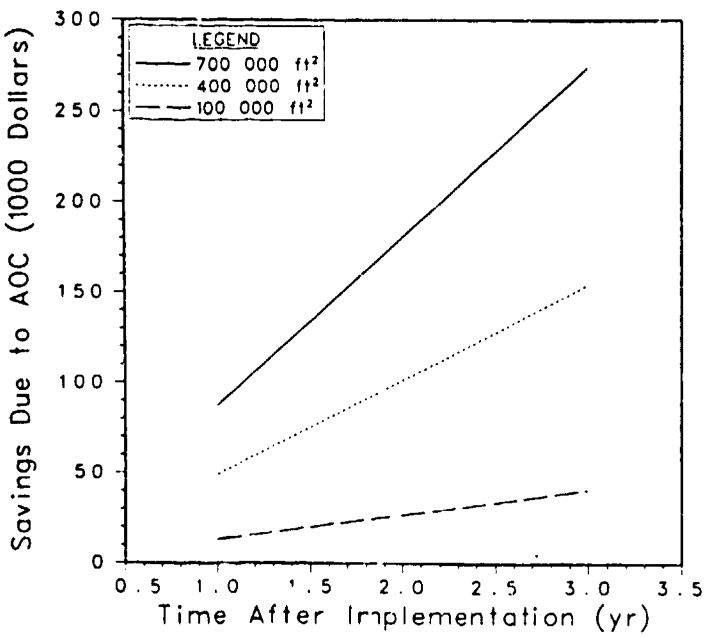

Fig. 11. Savings resulting from the application of AOC to office buildings in the Chicago area.

1. A standard building automation system as presently available from HVAC controls vendors is used as the base system.
2. There are very few cases in which it could be expected that a system for a large building application would have sufficient excess capability to run AOC as well as the tasks normally given it. Therefore, the AOC algorithms are implemented in a separate computer tied through communication channels to the base system.
3. Communication between the base and AOC computers will require relatively minor modification to standard data and task programs.
4. It is assumed that the AOC computer will require 64,000, 16-bit words of memory and a disk for mass storage.
5. Although much of the AOC program is usable across buildings, custom programming will be required to adequately represent specific building configurations. It is assumed that 25% of the algorithms will require custom programming.
6. The cost of applying the AOC to increasingly larger buildings will increase due to greater application definition requirements and custom programming time. It is assumed the base program will not require significant modification. An increase of application and programming cost of 10% per 100,000 ft^2 is assumed.
7. Significant increases in the need for sensing or control points to implement the AOC beyond those normally installed are not expected.
8. Based on preliminary estimates by LASL, it is assumed that the base AOC program will represent 50,000 words of memory and will be programmed in a high-level language.

The AOC implementation is separated into fixed and variable costs. The former are estimated as follows.

1. Interface software	$ 12,000
2. Basic AOC software	
a. Application evaluation	50,000
b. Software	100,000
3. Hardware integration	10,000
4. Application testing	50,000
5. Quality assurance	40,000
Total	$262,000

These development costs must be distributed over the systems expected to be sold. A 3-year payback is assumed, and changing money valuation is not considered. It is expected that application will be to larger buildings, those presently using available energy packages. From this, the sales are suggested to be

1. First year	10 units
2. Second year	20 units
3. Third year	30 units
Total	60 units.

This results in a development cost distribution of $4,500 per installation for a 3-year payback to the manufacturer.

The variable cost of applying the AOC technique to a specific installation must be considered. First, software for the installation must be developed that is unique to the installation; this is estimated as follows for a 100,000 ft^2 building.

1. Application algorithms	$ 4,000
2. Software	10,000
3. Quality assurance	4,000
Total	$18,000

As noted previously, this cost is expected to increase as the building size increases for large building applications. For smaller, more uniform buildings such as schools, a flat rate of $5,000 for each application is assumed.

Hardware includes a computer and mass storage unit (magnetic disk). Two levels of hardware are first considered. One is a high-performance minicomputer and supporting disk. The second is a moderate-performance computer. The selection is a function of the computational requirements for the AOC, and this has not been determined for a real building application. A third value is given for the cost of a high-performance system based on microprocessors expected to be available in 2 to 3 years.

1.	High-performance computer and support (present)	$56,700
2.	Moderate-performance computer and support (present)	25,000
3.	High-performance computer and support (future)	10,000

These costs include operating system software. It is expected that these costs will remain relatively constant across system sizes.

The costs to the user of AOC implementation are then estimated based on the data developed above. These are given, as a function of building size, in Fig. 12. A curve is given for each level of computational hardware costs. It is noted once again that we assume that a building automation system is present. The cost of this system is not included in the values given.

Payback

The benefits a building owner can expect to obtain from applying adaptive optimal control to a building as compared to the cost of application will determine, in general, the success of the technique as a product. Data on both potential savings and implementation cost have been given. Although not universally accepted, the savings are frequently required to return the cost of the investment in three years or less in order to make the investment for energy saving equipment acceptable. This period is assumed here.

The two cost relations used are energy cost for heating and cooling plus domestic hot water, and computer system costs. In the case of energy, there is every reason to expect continued increases in energy costs, at least the 7% per year used in the previous data. Computer hardware for the levels of capability expected to be required is projected to maintain its present price and potentially decrease dramatically as a number of announced microprocessors become available. Application costs are not expected to rise significantly over the time considered as productivity increases gained through experience will offset increased personnel costs.

Using the results of the two preceding sections, the payback for AOC applications is estimated. This is shown in Fig. 13 for office buildings. These results show that the application of AOC is estimated to have a favorable payback at a 20% savings level for large office buildings at present high-capability computer hardware costs. The payback improves dramatically at projected high-capability computer costs.

Based on these results, it is concluded that there is a very good likelihood that the use of AOC can not only save significant energy, but also could be effective as a commercial product.

Conclusion

The AOC concept has been shown to provide a type of control at the actuator level in HVAC systems that is much like that in use today. However, the control parameters, such as gains and offsets, are determined at a system level and are determined so as to optimize the overall system. This overall system optimization results in a significant energy savings. Implementation is possible with currently available hardware and is economically attractive.

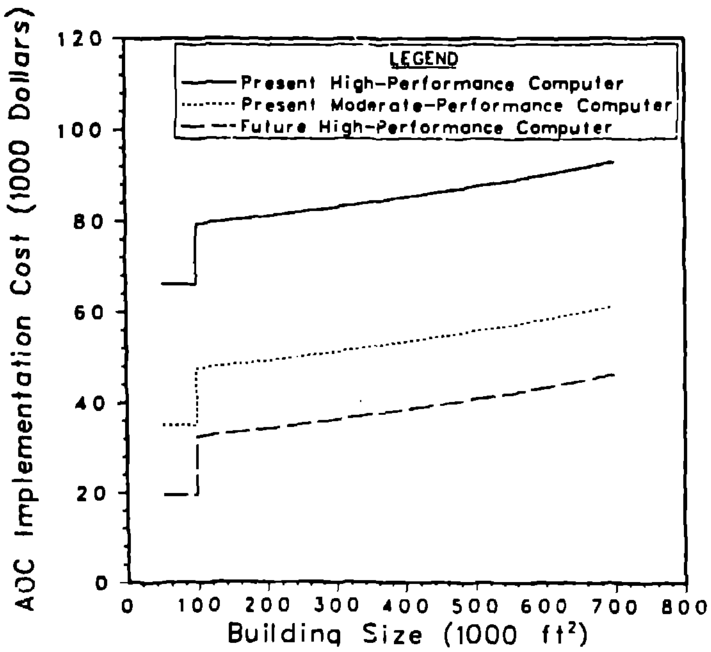

Fig. 12. AOC implementation cost as a function of building size.

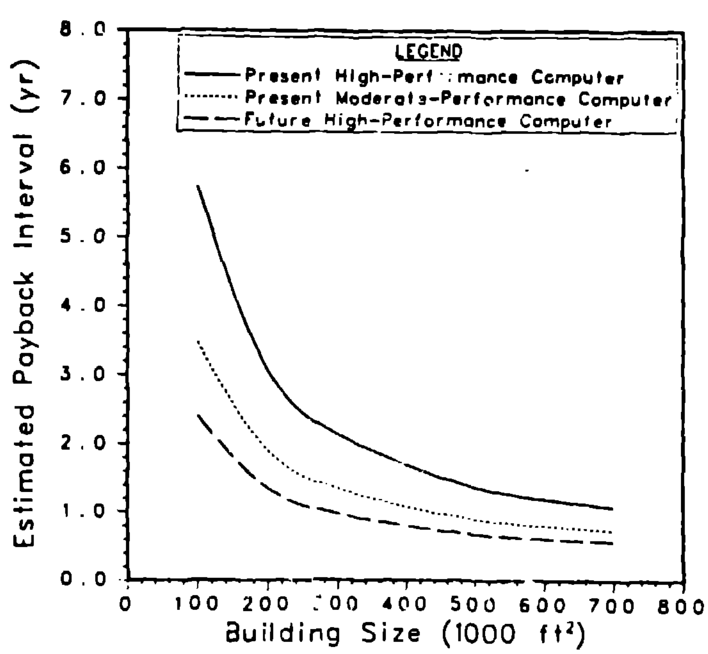

Fig. 13. Estimated payback interval for office buildings application of AOC.

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